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FLOOD-CONTROL OPERATION OF TENNESSEE VALLEY AUTHORITY RESERVOIRS

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By Edward J. Rutter,[1] M. ASCE

Synopsis

The reservoir system of the Tennessee Valley Authority (TVA), in Kentucky, Tennessee, North Carolina, Alabama, and Georgia, has become of increasing effectiveness in reducing flood stages since Norris Dam was closed in March, 1936. With the closure of Fontana Dam on the Little Tennessee River in 1944 and Kentucky Dam near the mouth of the Tennessee River in 1945, the reservoir system for flood control on the Tennessee River was practically completed. The first real tests of operation for flood reduction occurred in January, 1946, January, 1947, and February, 1948, when severe storms passed over the basin. These storms would have produced the fifth, sixth, and seventh highest natural floods, respectively, at Chattanooga, Tenn., if the reservoir system had not regulated the crest stages; and the floods of February, 1948, and January, 1946, would have been the fifth and the eleventh highest, respectively, on the lower Tennessee River in the vicinity of Kentucky Dam.

This paper describes the actual flood conditions and actual and alternative hypothetical operations of the tributary and main-river reservoirs during these floods. Reductions in peak stage and discharge at each dam and at critical points are tabulated, and comparisons are made between the actual crest reductions and possible reductions if other methods of operation had been followed.

Another flood on the Ohio and Mississippi rivers occurred in April, 1948, after the major flood season in the Tennessee Basin and when the TVA reservoirs were being filled to maximum normal levels. The effect of the reservoirs on this flood is also discussed.

Introduction

As a result of heavy rainfall occurring in the 3-day period from January 6 to January 8, 1946, serious flood conditions were produced along the Tennessee

Note.—Written comments are invited for publication; the last discussion should be submitted by October 1, 1950.

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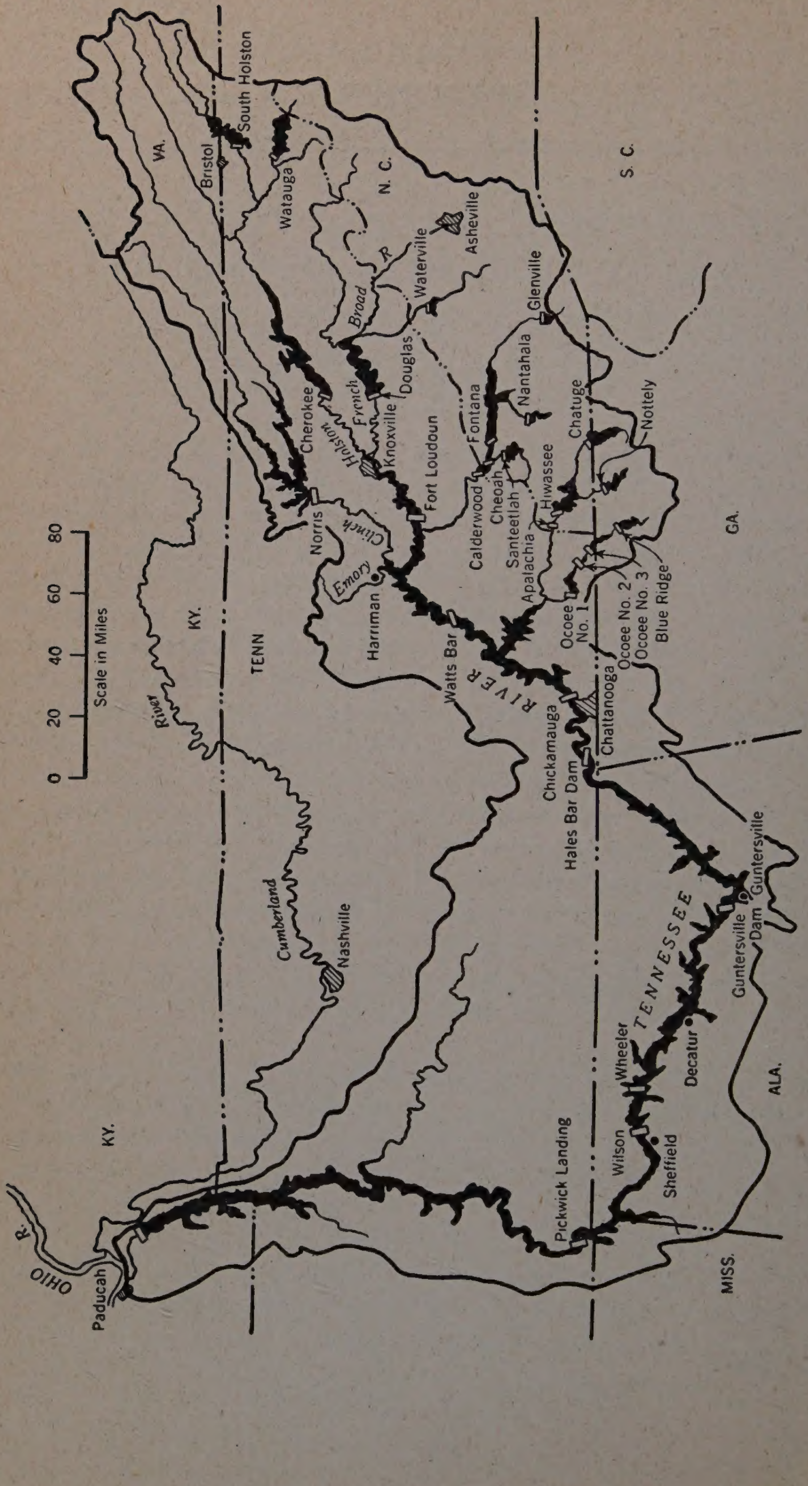

FIG. 1.—THE TENNESSEE RIVER SYSTEM

River and on the lower Ohio River at Cairo, Ill., about 30 miles west of Paducah, Ky. (see Fig. 1). In the following year (1947) another storm occurred in the 8-day period from January 14 to January 21, also producing serious flood conditions along the Tennessee River. Because the 1947 storm was relatively lighter on the lower Tennessee River Basin, that flood did not reach the same proportions on the lower Tennessee and Ohio rivers as did the 1946 flood. In February, 1948, for the third consecutive year, a storm occurred which would have caused damaging stages at Chattanooga and which would have produced record or near-record floods on some tributaries. Studies of the operation of the TVA reservoir system during these three floods show that peak stages were affected beneficially and that substantial savings in flood damages were obtained.

Rainfall

1946 Storm.—The rainfall (see Fig. 2) producing the 1946 flood occurred in two periods, the first lasting for about 3 days, and the second for about 1 day. In the first storm the average rain falling on the area below Chattanooga amounted to 5.62 in. and on the area above Chattanooga it amounted to 3.93 in. The highest average amount in one day was 2.61 in. below Chattanooga and 2.18 in. above Chattanooga. Minor amounts of rain fell later during the flood but these had little effect on the peak rates of flow. Between the two storms, additional rainfall was predicted which did not develop, particularly over the eastern section, and the predictions influenced the operation of the main-river reservoirs by requiring that a greater part of the available storage should be reserved.

1947 Storm.—The rainfall producing the 1947 flood was not as intense as that in 1946, the highest average amount falling over the area above Chattanooga in one day being 1.93 in. Below Chattanooga the greatest rainfall in one day was 1.09 in. The 1947 storm, however, extended over a longer time, and the total rainfall above Chattanooga was greater than it was in 1946. Rainfall was reported for 8 days continuously from January 14 to January 21, 1947, but the amounts reported on the first and last days were insignificant. The total average amount above Chattanooga was 6.07 in., and below Chattanooga it was 4.13 in. Daily rainfall in the 1947 storm also is shown in Fig. 2.

1948 Storm.—From February 5 to February 10, 1948, precipitation averaging less than 1 in. per day occurred over the Tennessee River Basin. On February 11, additional rainfall was predicted of generally less than 1 in. On the morning of February 12 greater amounts occurred than had been predicted, ranging to as much as 3 in. at some points. Succeeding forecasts indicated more rain and the actual rainfall was closer to the forecasts than on February 11. On the morning of February 13, as much as 4 in. or 5 in. was reported for the preceding 24 hours, and on the morning of February 14 amounts up to 2 in. or 2.5 in. were reported. The rainfall was generally heavier over the area below Chattanooga than on the area above Chattanooga, and also was much heavier below the tributary dams than above them. The Emory River Basin, with an area of 865 sq miles on which there is no reservoir control, received more than 7 in. in 3 days at some points and was a large contributor to the crest at Chattanooga.

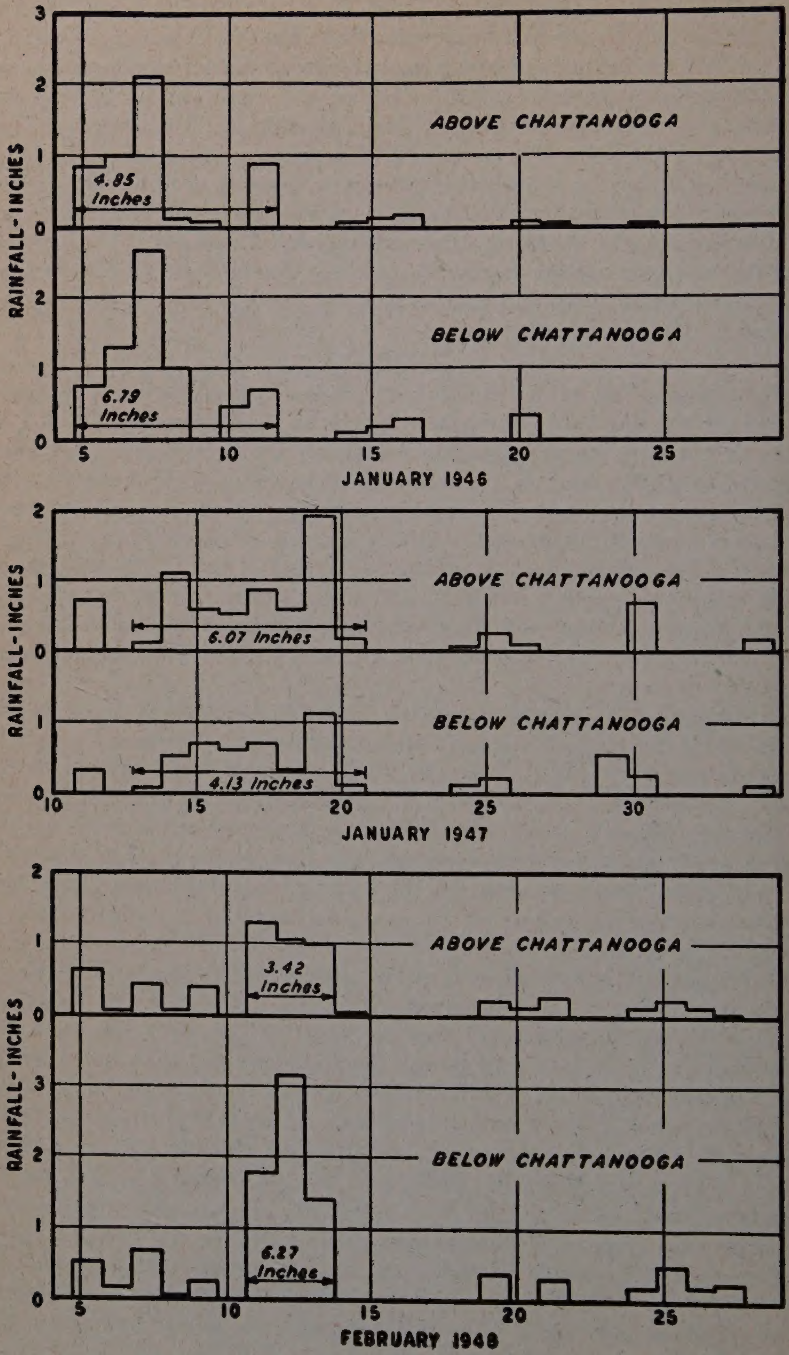

FIG. 2.—AVERAGE RAINFALL, TENNESSEE RIVER BASIN

The maximum daily rainfall above Chattanooga was 1.32 in. on February 12, and below Chattanooga it was 3.11 in. on February 13. The maximum point rainfall for a 24-hour period was 7.13 in. at Sugar Hill in the western part of the basin on February 12–February 13. Total rainfall for the 3-day period was 3.42 in. above Chattanooga and 6.27 in. below Chattanooga. Although the average above Chattanooga was only 3.42 in. in 3 days, some areas—notably the Emory Basin—received amounts comparable to those received on the lower basin.

Differences in the areal distribution of the storms above Chattanooga are shown by the amount of inflow stored in the tributary reservoirs (see subsequently in Table 3). The operation of the reservoirs was about the same during each flood—that is, small releases for power generation were made as required, but the relative amount stored in Cherokee and Fontana reservoirs was substantially more in the 1947 flood than in the 1946 flood, and substantially less was stored in Norris and Douglas reservoirs. The 1946 storm, however, was more intense over the area between Chickamauga and Watts Bar dams, more than 5 in. being reported for 1 day at several stations.

Tributary Reservoir Operation

The function of the tributary reservoirs in a flood-control operation is to retain that part of their inflow which would contribute to the flood at Chattanooga, and to release the stored water as soon as practicable after the flood. In great floods it will not be possible to retain all inflow. Consequently, some discharge will be made in the early part of each flood so that, in case the flood should develop into an extreme one, all storage capacity will not have been filled before the peak inflow occurs. The amount of this early discharge will vary with the reservoir stage. Flood-storage capacity reserved on March 15 at seven tributary reservoirs is given in Table 1.

TABLE 1.—Flood-Storage Capacity on Some Tennessee Valley Authority Reservoirs As of March 15

Reservoir (see Fig. 1)	Drainage area, in square miles	Flood-Storage Reservation: In acre-feet	Flood-Storage Reservation: In inches
Cherokee	3,429	807,200	4.41
Douglas	4,541	1,019,800	4.21
Fontana	1,571	581,800	6.94
Norris	2,912	1,377,000	8.87
Hiwassee	968	245,100	8.13
Chatuge	189	75,100	7.45
Nottely	214	83,500	7.32

1946 Flood.—During the month of December, 1945, tributary reservoirs were drawn to normal flood-season levels for January 1, by substantial releases through the sluice gates. At the beginning of the 1946 storm on January 5, all tributary reservoirs were at or below the normal level for that date. During the flood, releases of water were limited to power production until after the peak stage was reached at Chattanooga (about January 10) when additional water was released through the sluices to reduce the reservoirs to normal levels. These levels were reached about 15 days or 20 days after the beginning of the flood.

Normal level is defined in this paper as the maximum level to which the reservoir may rise except during a flood-control operation. This level varies

with the season of the year. For the tributary reservoirs it increases from January 1 to March 15 and then rises more rapidly to April 1. After April 1 the reservoirs may be filled to within a few feet of the top of spillway gates if there is sufficient stream flow, but they must be lowered during the summer and fall to the level for January 1.

1947 Flood.—In the fall of 1946 stream flow was below normal and the demand for power production was high. The tributary reservoirs, therefore, were reduced to levels substantially below normal for January 1, except in the case of Douglas Reservoir which was drawn to normal level by sluice gate releases. A small amount of runoff resulted from a storm on January 1, 1947, and the reservoirs were partly filled to their normal levels. At the beginning of the flood on January 14, 1947, the levels were still below normal, except that of Douglas Reservoir which was 2.7 ft above normal. Releases were limited to requirements for power production until January 23, flood danger at Chattanooga then being over, when additional releases were made through the sluices to return the reservoirs to normal levels. As in the 1946 flood, these levels were reached from 15 days to 20 days after the beginning of the flood.

1948 Flood.—At the beginning of February, 1948, the tributary reservoirs were substantially below their normal flood-season levels, having been drawn down in the preceding dry season for power generation. Some recovery in these reservoirs was possible from the runoff due to the rainfall on February 5 to February 10; but even on February 11, at the beginning of the heavy rainfall, Cherokee Reservoir was about 28 ft below normal; Norris Reservoir, about 30 ft; Fontana Reservoir, about 66 ft; Douglas Reservoir, 3 ft; Hiwassee Reservoir, 29 ft; Chatuge Reservoir, 22 ft; and Nottely Reservoir, 38 ft.

During the flood the entire inflow into the tributary reservoirs was stored except for a small amount used for power generation. The amount so released was only about 6% of the water passing Chattanooga at the flood crest. Much greater inflows could have been stored in the tributary reservoirs because, with the exception of Douglas Reservoir, by the end of the flood the water level had not risen to the normal flood-season level. Douglas Reservoir rose about 14 ft above its normal level but was lowered after the flood at discharge rates up to 19,500 cu ft per sec and by March 4 was returned to its normal level. The other tributary reservoirs continued to rise slowly after the flood. Table 2 shows the normal and actual headwater elevations for the three floods, the maximum level reached during each flood, the amount stored, and the remaining available storage. Storages are given in acre-feet and in inches over the tributary drainage area. The flood storage available at the beginning of each flood is the sum of the maximum amount stored and the remaining available storage shown in Table 2. Fig. 3 shows the actual elevations and discharges of the tributary reservoirs in the 1946 flood. Operations in the floods of 1947 and 1948 followed a similar pattern and are not shown.

These tributary water-control operations eliminated damage to the areas immediately below the dams, and at the end of the flood there was from two times to four times as much storage space remaining as had been filled during the flood.

The quantities of water actually stored, shown in Table 2, are maximum amounts but these amounts were not completely effective in every case in reducing the flood peak at Chattanooga. From January 8 to January 14, 1946, inclusive, and from January 17 to January 26, 1947, the actual discharges at Chattanooga were lower than the computed natural discharges. During the flood period from February 13 to February 19, 1948, the actual Chattanooga

TABLE 2.—TRIBUTARY STAGES FOR SOME TENNESSEE VALLEY AUTHORITY RESERVOIRS

Reservoir (Fig. 1)	Normal elevation[a]	Actual elevation[a]	Maximum elevation reached	Maximum Amount Stored		Remaining Storage[b]	
				1,000 acre-ft	Inches	1,000 acre-ft	Inches
(a) 1946 Flood							
Cherokee....	1,021.8	1,021.1	1,037.5	245	1.34	888	4.86
Douglas.....	936.9	935.3	964.9	408	1.69	901	3.72
Fontana.....	1,617.4	1,615.9	1,637.5	138	1.65	628	7.50
Norris......	979.0	978.4	995.3	377	2.43	1,249	8.05
Chatuge.....	1,910.5	1,909.1	1,914.3	26	2.53	77	7.65
Nottely.....	1,744.0	1,749.4	1,760.5	28	2.48	64	5.61
Hiwassee....	1,456.4	1,456.1	1,468.9	34	1.13	254	8.44
Total.....	....	....	....	1,256	1.75	4,061	5.69
(b) 1947 Flood							
Cherokee....	1,024.0	998.6	1,036.4	451	2.47	907	4.95
Douglas.....	939.2	941.9	972.6	488	2.02	752	3.11
Fontana.....	1,620.3	1,589.2	1,639.4	296	3.54	614	7.34
Norris......	980.2	969.5	993.2	491	3.17	1,300	8.38
Chatuge.....	1,911.1	1,904.0	1,911.8	35	3.48	97	9.63
Nottely.....	1,745.2	1,737.1	1,752.3	31	2.72	90	7.89
Hiwassee....	1,458.1	1,439.8	1,479.2	102	3.38	222	7.37
Total.....	....	....	....	1,894	2.65	3,982	5.57
(c) 1948 Flood							
Cherokee....	1,032.5	1,005.0	1,029.8	292	1.60	1,013	5.55
Douglas.....	948.0	945.0	964.6	296	1.23	907	3.76
Fontana.....	1,631.5	1,565.0	1,598.5	154	1.84	863	10.30
Norris......	984.8	955.0	982.5	469	3.02	1,543	9.97
Chatuge.....	1,913.4	1,891.5	1,898.0	20	1.98	153	15.20
Nottely.....	1,749.8	1,711.5	1,728.2	20	1.76	135	11.82
Hiwassee....	1,464.6	1,435.6	1,456.7	45	1.49	287	9.55
Total.....	....	....	....	1,296	1.81	4,901	6.85

[a] At noon on January 6, 1946, January 14, 1947, and February 11, 1948. [b] Between the maximum elevation reached during the flood and the maximum controlled elevation.

discharge was less than the natural discharge. It was also less than the natural discharge before and after these dates, but this 7-day period represents the time when tributary inflow should have been retained for the benefit of Chattanooga. The amounts stored in the tributary reservoirs during these periods, allowing for a time of travel to Chattanooga, represent more correctly the relative control afforded by each of the reservoirs.

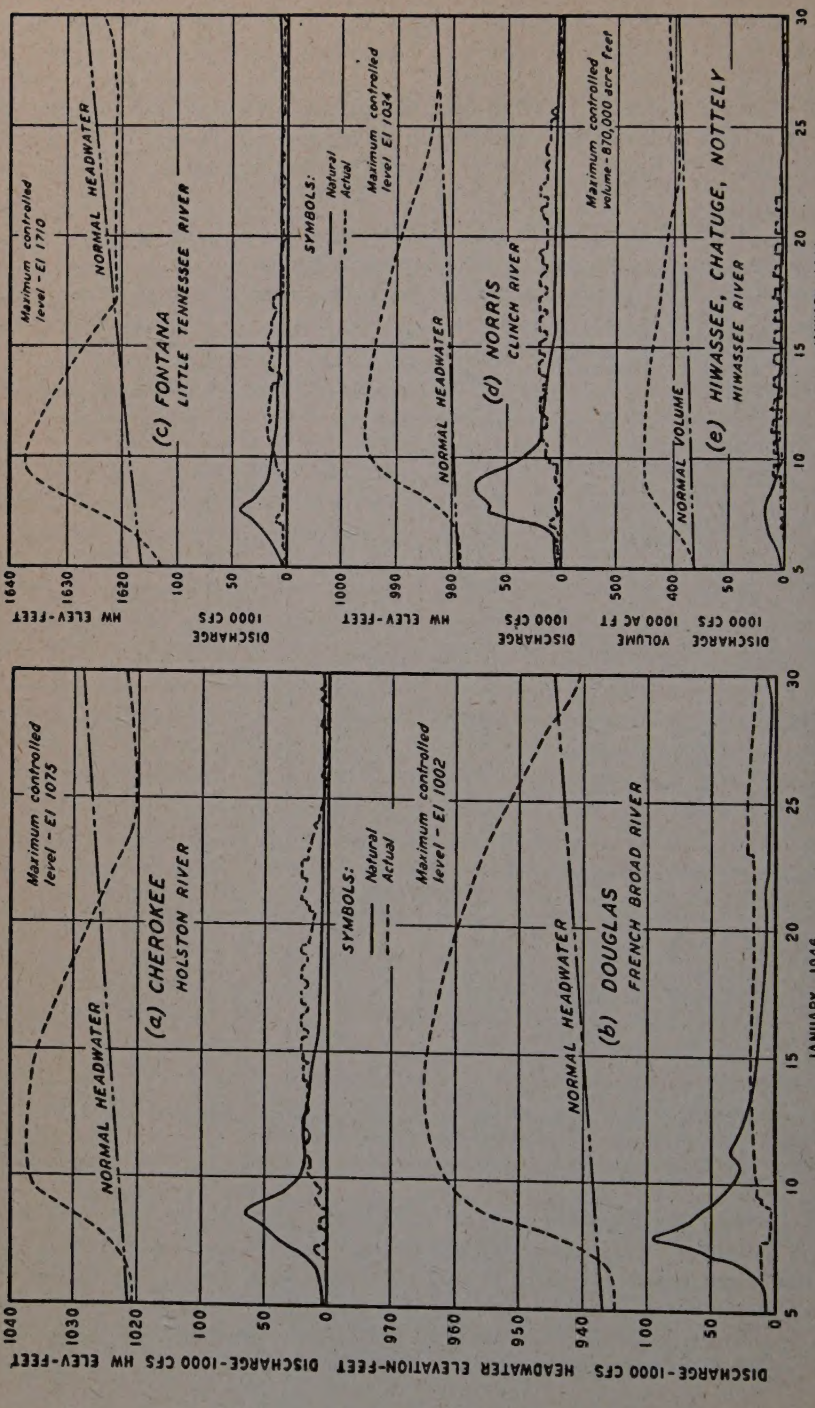

FIG. 3.—OPERATION OF TRIBUTARY RESERVOIRS; 1946 FLOOD

Table 3 shows the amount of inflow and outflow, storage in the reservoirs, the percentage of the inflow stored at each reservoir, the amount of water stored in each reservoir expressed as a percentage of the total amount stored in all reservoirs, and the area above each reservoir expressed as a percentage of the total controlled drainage area. These amounts are for the flood periods given previously; but, if a shorter period near the crest of the flood were assumed, a greater proportion of tributary inflow would be effective because at the end of the selected periods releases to return the reservoirs to their normal

TABLE 3.—EFFECTIVE TRIBUTARY STORAGE FOR SOME TENNESSEE VALLEY AUTHORITY RESERVOIRS

Reservoir	Assumed time of travel to Chattanooga, Tenn., in days	Thousand Acre-Feet			Storage		Percentage of controlled drainage area
		Inflow	Outflow	Storage	Percentage of inflow	Percentage of total	
(a) 1946 Flood							
Cherokee	3	354	100	254	72.0	21.3	25.6
Douglas	3	530	142	388	73.3	32.6	33.9
Fontana	2	250	136	114	45.5	9.6	11.7
Norris	2	510	134	376	73.7	31.5	21.6
Hiwassee	1	133	73	60[a]	45.1	5.0	7.2
Total		1,777	585	1,192	67.2	100.0	100.0
(b) 1947 Flood							
Cherokee	3	557	106	451	81.0	25.0	25.6
Douglas	3	642	154	488	76.0	27.1	33.9
Fontana	2	358	76	282	78.8	15.6	11.7
Norris	2	637	169	468	73.4	25.9	21.6
Hiwassee	1	197	82	115[a]	58.4	6.4	7.2
Total		2,391	587	1,804	75.5	100.0	100.0
(c) 1948 Flood							
Cherokee	3	348	47	301	86.5	22.8	25.6
Douglas	3	395	91	304	77.0	23.0	33.9
Fontana	2	186	32	154	82.8	11.6	11.7
Norris	2	502	25	477	95.0	36.1	21.6
Hiwassee	1	108	22	86[a]	79.6	6.5	7.2
Total		1,539	217	1,322	86.0	100.0	100.0

[a] Includes storage in Chatuge and Nottely reservoirs.

levels had been begun. For example, in the 1947 flood if a period corresponding to the 3-day period of January 20–January 22 at Chattanooga had been assumed, more than 83% of the inflow would have been stored, compared with 75.5% for the longer period.

The storage of 86% of the inflow during the 1948 flood represents a high degree of control; and it compares with 67% stored in the January, 1946, flood and with 75% stored in the January, 1947, flood. Such a degree of control was possible because of the low reservoir stages at the beginning of the flood and will not necessarily be obtained in all future floods.

Table 3 also shows that in all three floods only Norris Reservoir stored water above its drainage area ratio. Fontana Reservoir in 1947 was the only other instance when more was stored with respect to its drainage area.

Tennessee Main-River Reservoir Operation

The function of the main-river reservoirs in relation to a flood-control operation is to hold the headwater level at its minimum, or to lower it to that minimum in the early part of the flood and then to fill the reservoir during the period of peak inflow. The rate and degree of filling will depend on stream flow and rainfall predictions. As in the case of tributary reservoirs, the stored water is to be released as soon as practicable after the flood, considering flood conditions on the Tennessee, Ohio, and Mississippi rivers. The main-river reservoirs above Chattanooga are operated with that city as the primary consideration. Those below Chattanooga are operated primarily for reducing flood crests downstream from each dam, and for regulating the flow on the lower Ohio and Mississippi rivers.

The nominal flat-pool flood storage during the winter months in eight main-rivers reservoirs is as given in Table 4.

TABLE 4.—Flood-Storage Reservation on Some Tennessee Valley Authority Reservoirs During the Winter Months

Reservoir	Drainage Area, in Square Miles		Flood-Storage Reservation	
	Each	Between dams	Acre-feet	Inches
Fort Loudoun	9,550	1,580	109,300	1.30
Watts Bar	17,310	3,277	377,600	2.16
Chickamauga	20,790	2,512	329,400	2.46
Guntersville	24,450	3,660	162,900	0.83
Wheeler	29,590	5,140	347,500	1.27
Wilson	30,750	1,160	52,500	0.85
Pickwick	32,820	2,070	418,400	3.79
Kentucky	40,200	7,380	4,010,800	10.19

In all studies of operation of these reservoirs, storage under a sloped profile was used. During a flood this may be substantially different from the flat-pool storage in Table 4.

1946 Flood.—At the beginning of the 1946 flood all main-river reservoirs were slightly above normal level, but within the range permitted. Normal level in the main-river reservoirs is constant from January 1 to March 15 or March 31, having been established by navigation requirements. After March 15 (or March 31) the level increases to within a few feet of the top of the gates, but later in the year it must be lowered to the level for January 1. During the 1946 flood no attempt was made to lower the three reservoirs above Chattanooga (Fort Loudoun, Watts Bar, and Chickamauga) to the minimum levels, and only part of the available storage space was filled after the flood commenced. Because of the continued prediction of additional rainfall, these reservoirs were held ready for storage of any additional inflow that might have developed. Operation of these reservoirs aided in reducing the peak at Chattanooga; but, because they were drawn down to initial levels soon after the

peak, the reservoirs did not reduce the flood volume during the 7-day period from January 8 to January 14.

Guntersville headwater level at the dam fluctuated between El. 593 and El. 594 throughout the 1946 flood period. Because of lack of excess spillway capacity at low levels, Wheeler Reservoir rose about a foot before controlled storage was needed for peak reduction. The maximum headwater elevation reached was slightly above El. 554. At Pickwick Reservoir about 5 ft of storage space was used, and the discharge was increased to about 350,000 cu ft per sec. This reservoir was then lowered to discharge the previously stored water before the Ohio River crest arrived. When storage for Cairo peak reduction was required, Pickwick Reservoir was again filled to about El. 414.

On January 5, 1946, Kentucky Reservoir headwater was at its minimum navigation level for low flows. On January 6, when it was recognized that a substantial storm and a flood were developing, it was possible to lower Kentucky Reservoir at the dam without interfering with navigation requirements at upstream points. The release was increased from about 86,000 cu ft per sec to about 200,000 cu ft per sec. Beginning on January 8, when it became apparent that a 35-ft stage at Cairo would be exceeded and that much higher stages were possible, the discharge was further increased to about 400,000 cu ft per sec, in an attempt to draw the reservoir down to El. 346 at the rate of 1 ft per day. The rate of drawdown of 1 ft per day was not maintained, however, because of the rapid increase in inflow. The minimum elevation, El. 346, was not reached because of the necessity for storing to reduce the Cairo peak stage. Beginning on January 13, the discharge was decreased to about 264,000 cu ft per sec over a period of 3 days and then held uniform at that rate for about a week. The maximum reservoir level was El. 359.3 on January 19.

Actual discharges and reservoir elevations at the main-river dams are shown in Figs. 4 to 8.

1947 Flood.—Operation of the main-river reservoirs in the 1947 flood was generally similar to that in the 1946 flood. At the beginning of the 1947 flood (January 14) the reservoirs were at, or slightly above, their normal levels. The three reservoirs above Chattanooga were allowed to rise slightly above those levels until January 17 or January 18 when, in view of the continual rain and predictions of rain, drawdown to approximate normal levels was commenced. On January 20, the intense rain required the use of some of the available storage to prevent damaging stages at Chattanooga. However, a substantial volume of the available storage was held in reserve for possible additional runoff.

Guntersville Reservoir was allowed to rise slightly above normal level (El. 593) from January 14 to January 18, 1947; then it was drawn down to below El. 593 on January 19; and finally it was filled to the maximum level by January 22, during the period of high inflow. Wheeler Reservoir rose a small distance above normal level (El. 550) until January 20 and then, by holding a steady discharge, the reservoir rose to El. 554.2 on January 23. Pickwick Reservoir was drawn down from El. 410 on January 13 to El. 407.7 on January 20 and then filled to El. 410 on January 23. Complete use of the available storage was not required because of the low stages at Cairo.

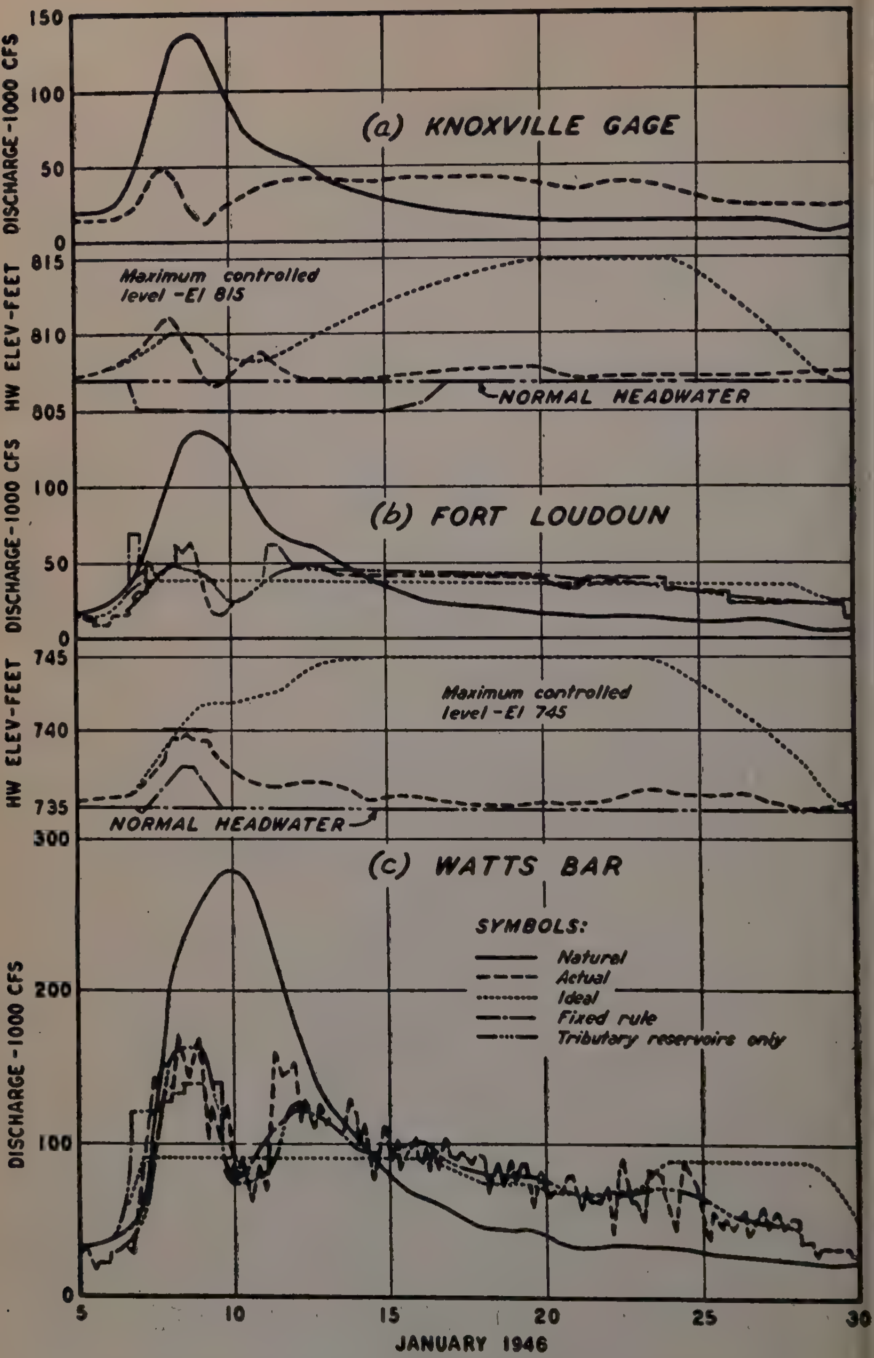

FIG. 4.—KNOXVILLE (TENN.) GAGE, AND OPERATION OF FORT LOUDOUN AND WATTS BAR RESERVOIRS IN TENNESSEE; 1946 FLOOD

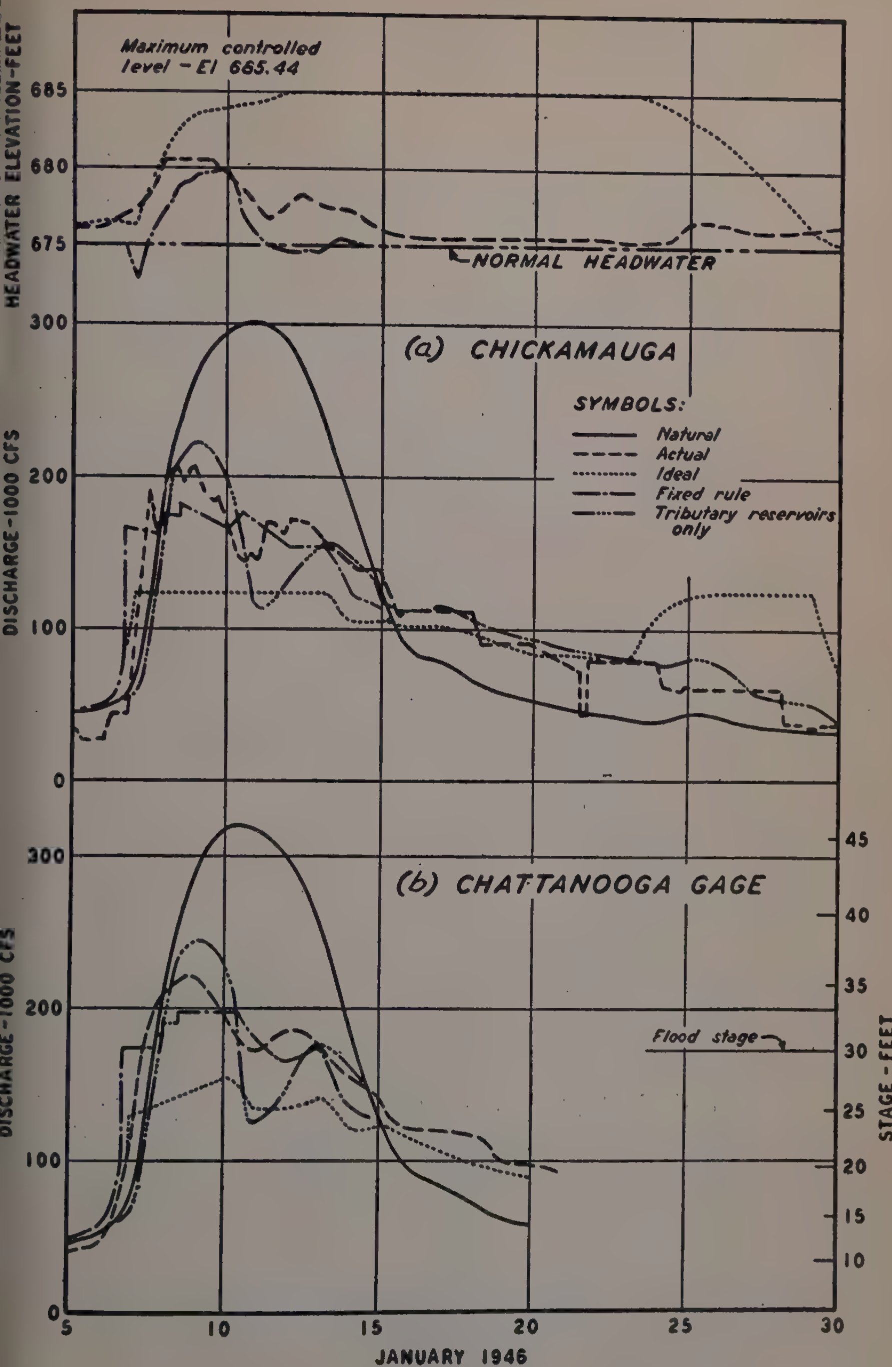

FIG. 5.—CHATTANOOGA (TENN.) GAGE, AND OPERATION OF CHICKAMAUGA RESERVOIR IN TENNESSEE; 1946 FLOOD

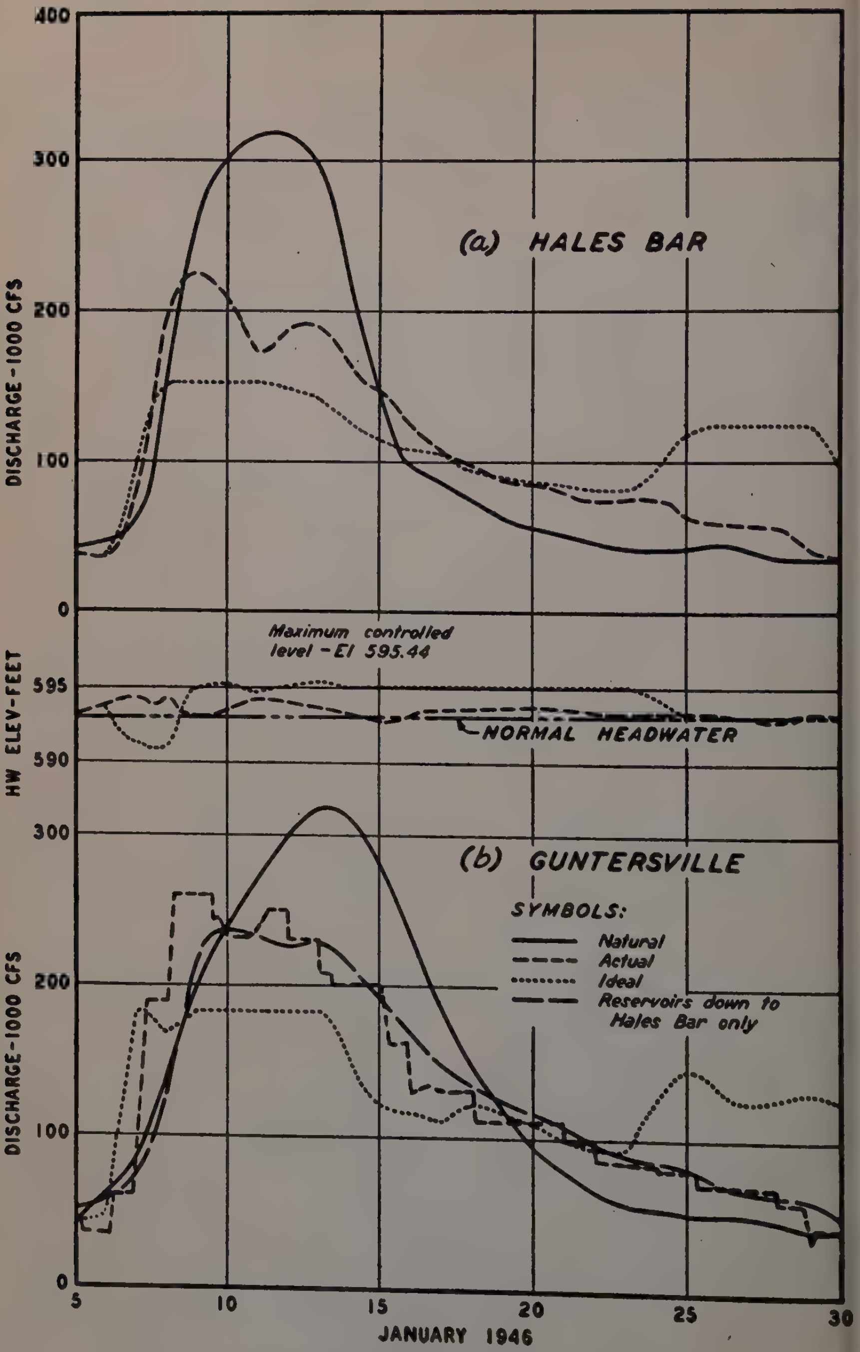

FIG. 6.—OPERATION OF HALES BAR RESERVOIR IN TENNESSEE AND GUNTERSVILLE RESERVOIR IN ALABAMA; 1946 FLOOD

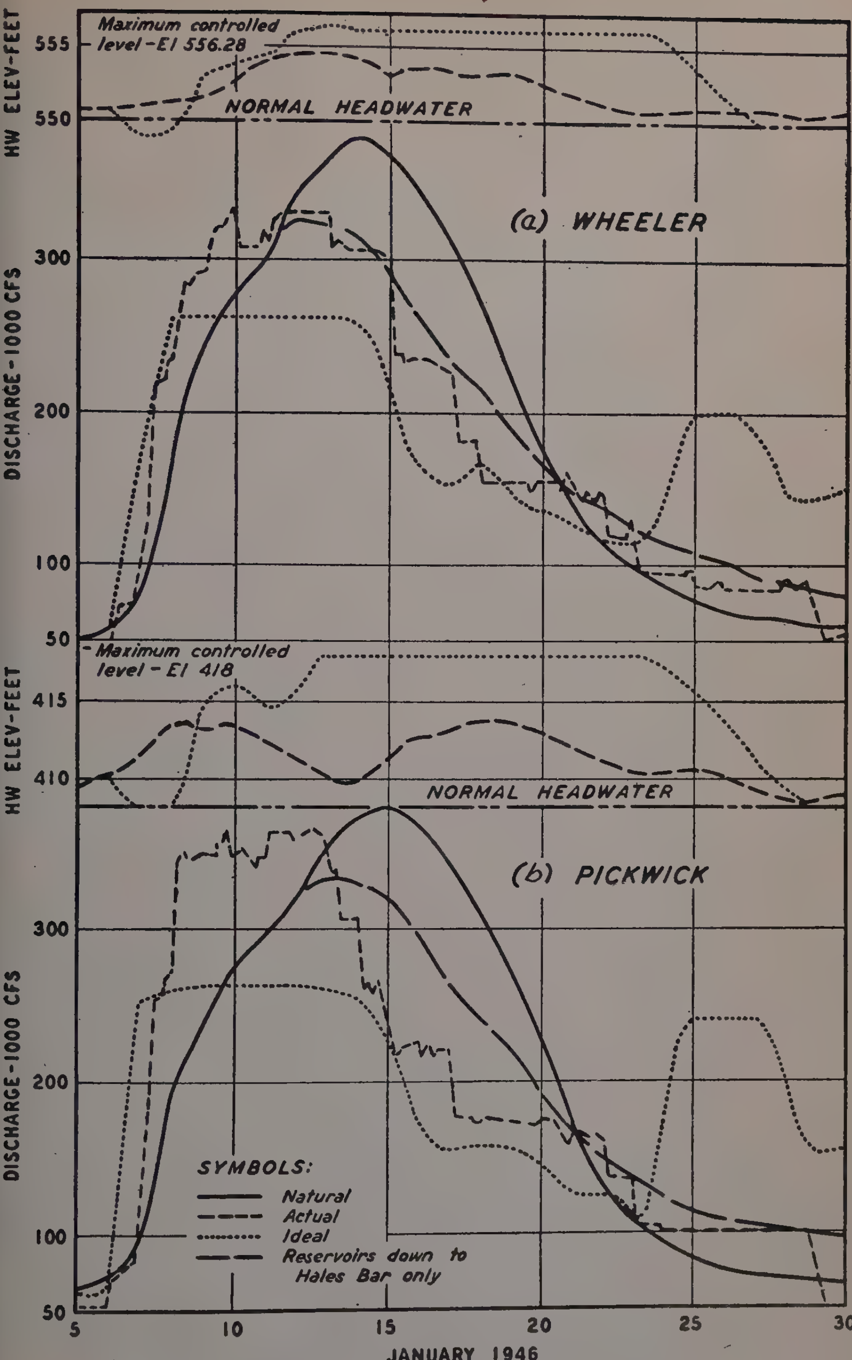

FIG. 7.—OPERATION OF WHEELER RESERVOIR IN ALABAMA AND PICKWICK RESERVOIR IN TENNESSEE; 1946 FLOOD

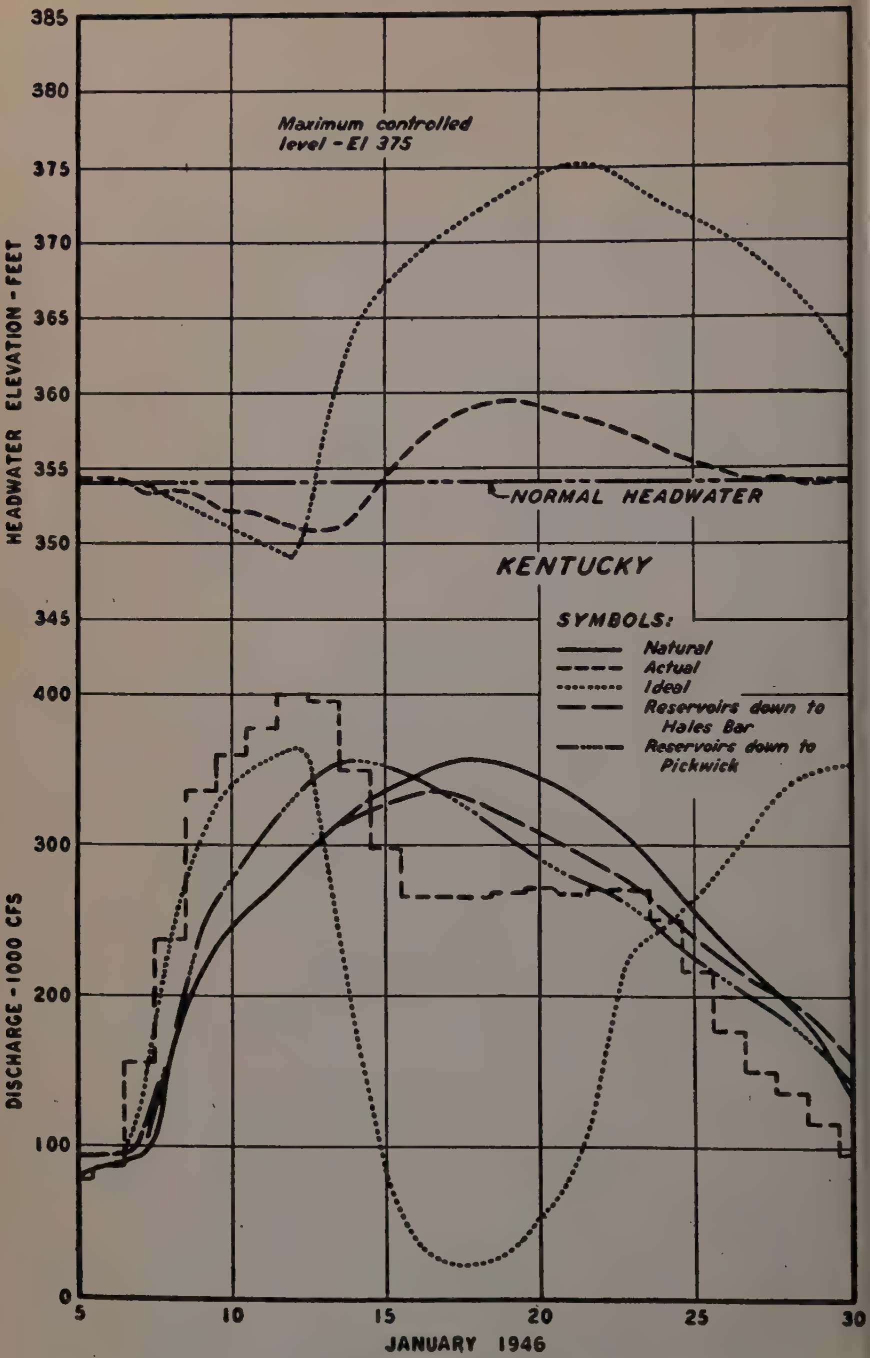

FIG. 8.—OPERATION OF KENTUCKY RESERVOIR IN KENTUCKY; 1946 FLOOD

Kentucky Reservoir was held at about normal elevation until January 18, 1947. On this date the Cairo stage stood at about 30 ft and drawdown of the reservoir was begun. In the 1946 flood, drawdown was started when the Cairo stage reached 35 ft, but it was found that drawdown should have been begun earlier to accomplish complete drawdown to El. 346. In the 1947 flood drawdown was begun sooner, therefore, in the attempt to reach the minimum level. On January 22, it was believed that the Cairo stage would not approach serious proportions and drawdown was stopped. Thereafter, Kentucky Reservoir was refilled to its normal level, El. 354, by February 3.

1948 Flood.—The main-river reservoirs were all at or close to their normal flood-season levels on February 5. Some slight filling then occurred because of the rainfall from February 5 to February 10. By February 11, however, these reservoirs had been returned to within 1 ft of their normal levels.

The three reservoirs above Chattanooga were utilized during the major flood period to control as much of the runoff from the area below the tributary dams as was prudent in view of the continued prediction of rainfall. Fort Loudoun was filled to about El. 810, Watts Bar to El. 742, and Chickamauga to El. 682.5. These reservoirs were promptly returned to their normal levels at gradually decreasing discharge rates after the crest had passed Chattanooga.

The main-river reservoirs below Chattanooga were operated to keep the discharge below each of the dams as low as possible, bearing in mind the possibility of a serious flood on the Ohio and Mississippi rivers. Guntersville and Wheeler reservoirs were almost completely filled, and the combined regulation of all reservoirs lowered the flood-crest discharges and stages below those two dams.

Wilson Reservoir was held at approximately the gate top level (El. 507.88); but, because of the excessive rainfall in that vicinity, it rose above that level and then at the height of the flood was drawn down to slightly below gate top level.

Pickwick Reservoir was practically filled to El. 418 by February 14 but was lowered immediately to be ready for a flood on the lower Ohio and Mississippi rivers.

The headwater at Kentucky Reservoir was lowered from El. 354 on February 13 to less than El. 350 on February 22, and then was raised in anticipation of the crest at Cairo. Stages at Cairo did not reach the point where a full flood-control operation was required at Kentucky Reservoir. Actual discharges and reservoir elevations at the main-river dams are shown in Figs. 4 to 8 for the 1946 flood.

NATURAL DISCHARGE

Natural discharge hydrographs for the three floods were computed at all multiple-purpose dams and at other critical points of flooding. "Natural discharge" means the discharge that would have occurred if these dams had not been built. Natural hydrographs at the smaller tributary reservoirs (Apalachia, Blue Ridge, Ocoee No. 1, Ocoee No. 2, Ocoee No. 3, the Alcoa reservoirs, and other small reservoirs) were not computed, and the effect of these reservoirs was disregarded in computing natural hydrographs at downstream points. The combined effect of these smaller reservoirs might be

equivalent to as much as 1 ft on the Chattanooga gage. No attempt was made to determine the effect of Wilson Reservoir because of its small flood-storage capacity. At Hales Bar Dam there was no controlled flood storage and the effect of this reservoir is similar to that of a natural reach of the river.

Natural discharge, or reservoir inflow, on each major tributary was computed by combining the change in storage in each 6-hour period and the actual discharge during the same time, adding the two amounts if the reservoir was rising and subtracting the change in storage from the actual discharge if the reservoir was falling. The discharge thus computed is the total during the 6-hour period. However, for constructing a hydrograph it was assumed that this amount was a rate of flow occurring at the midpoint of the 6-hour period.

Check computations of the natural tributary hydrographs were made from rainfall data and upstream flow records by a method developed from pre-reservoir storms and floods. These check hydrographs agreed closely with those computed from reservoir-storage increments and actual discharge thus indicating, in the case of the large tributary reservoirs, that there was little difference between natural discharge and reservoir inflow.

Natural and actual discharges, in cubic feet per second, on the five major tributaries are shown in Fig. 3 for the 1946 flood. Actual headwater levels at the dams and normal maximum headwater levels are also shown. For Hiwassee River, the total volume in the three reservoirs (Hiwassee, Chatuge, and Nottely) is used because these were considered to act as a unit.

On the main Tennessee River the first step in the computation of natural discharge was the determination of the unmeasured flow into each reservoir by combining the reported daily discharges at the upstream dams and the tributary gaging stations, the discharge at the downstream dam, and the daily change in storage as represented by the change in headwater level and flow-storage curves. In this procedure a standard routing form was used, the reported discharges and headwater elevations were entered on the form, and the corresponding storage was read from the flow-storage curves. From these amounts the total inflow into the reach was computed; and, since the measured proportion of the total was known, the unmeasured flow was determined. Next, the natural tributary flows were combined with the unmeasured flow into the main-river reaches and their sum was routed downstream through the successive reaches with the aid of natural routing diagrams.[2] Natural discharges at the main-river dams and at Knoxville, Tenn., and Chattanooga are shown in Figs. 4 to 9 for the 1946 flood. Stages instead of discharges are shown at Paducah and Cairo, on the Ohio River.

The method used to compute inflow uses reservoir-volume curves which, of course, are mass curves. The difference between two points on the curve is the rate of increase in storage and an error made in reading a volume at a certain time would affect the inflow for two periods only, and would be compensating. Routing computations were checked by comparing total inflow with total outflow during the flood period, with consideration given to changes in storage. Computed natural discharge hydrographs were compared with hydrographs

[2] "Flood Routing," by Edward J. Rutter, Quintin B. Graves, and Franklin F. Snyder, *Transactions*, ASCE, Vol. 104, 1939, p. 275.

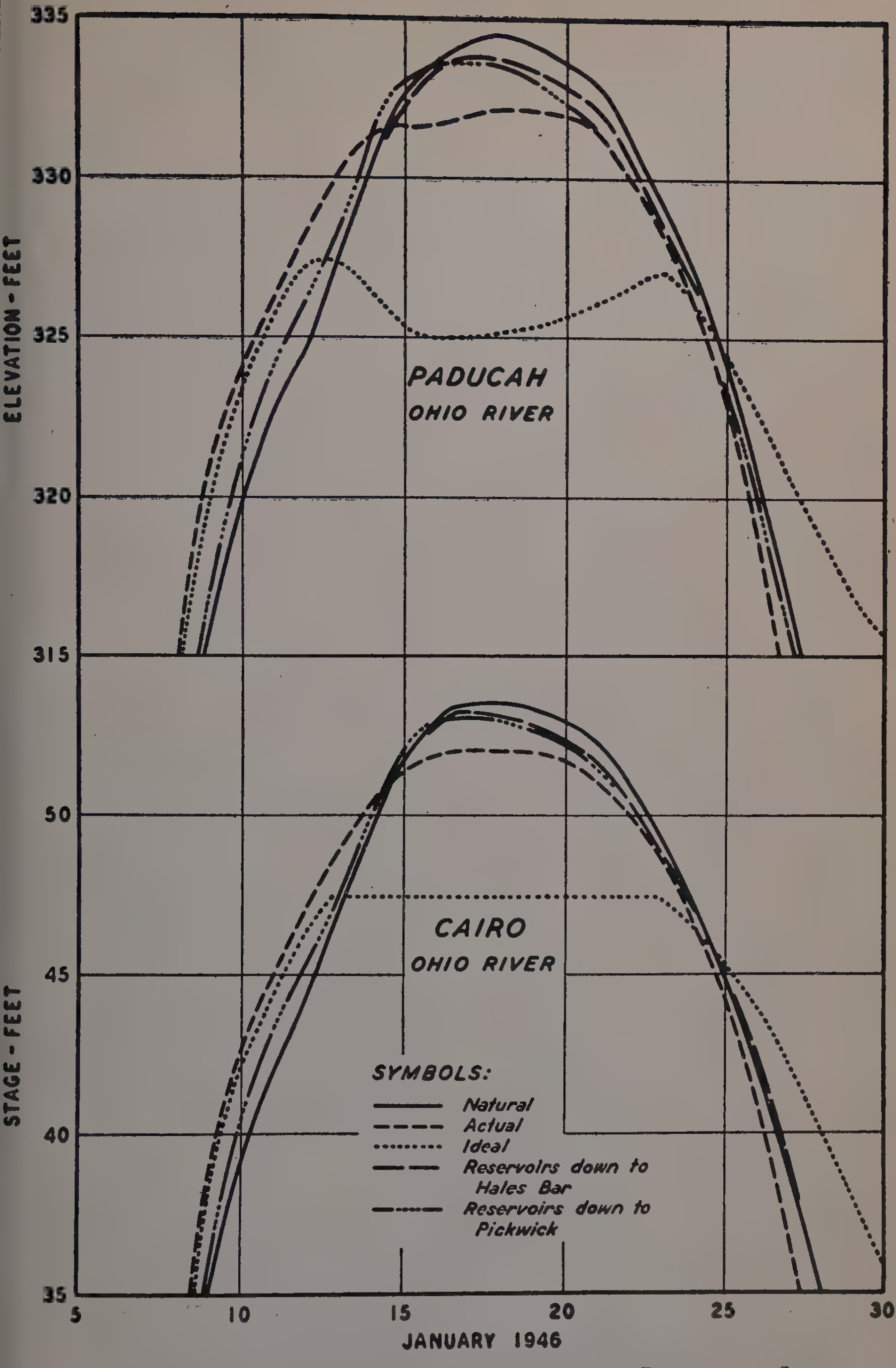

FIG. 9.—EFFECT OF OPERATION OF TENNESSEE VALLEY AUTHORITY RESERVOIRS ON STAGES AT PADUCAH, KY., AND CAIRO, ILL.; 1946 FLOOD

of floods occurring before the reservoirs were built to detect any inconsistency. A comparison of total flood volume with average rainfall also affords an overall check of the computations.

Peak Reductions

Maximum discharges and stages and peak reductions for the three floods are given in Table 5. The difference between the actual and the natural hydrographs shown in Figs. 3 to 9 for the 1946 flood is the effect of the operation of the reservoir system.

The actual stages in Table 5 reflect the combined result of upstream storage, the backwater effect from a downstream dam, and the effect of lowering the water surface by channel improvement. As would be expected, the greatest reductions in stage occur immediately downstream from the large tributary reservoirs and, generally, reductions become smaller as the Mississippi River is approached.

Natural stages were obtained by applying the computed natural discharge to the rating curve applicable to each location before the construction of the dam.

In the 1946 flood the natural volume at Chattanooga for the 16-day period from January 5 to January 20, inclusive, would have amounted to 2,554,000 day-sec-ft. With an allowance for an average base flow of 34,000 cu ft per sec per day, this volume is equivalent to a runoff of 3.50 in. from the rainfall of 4.85 in., or 72%.

The contribution of the 600-sq-mile area between Chickamauga Dam and the Chattanooga gage was determined by subtracting the reported daily discharge at the dam from the discharge corresponding to the Chattanooga stage, consideration also being given to the stream gage record on South Chickamauga Creek. To establish the natural Chattanooga discharge, the local contribution determined from actual flows was added to the computed natural discharge at Chickamauga. This local contribution has become of great importance because it comes from the only part of the area above Chattanooga over which there is no control. The 600-sq-mile area is only 2.8% of the total area above Chattanooga; but in the 1946 flood it contributed 22,000 cu ft per sec, or about 10%, to the actual peak and 30,000 cu ft per sec (also about 10%) at the time the natural peak would have occurred. A discharge of about 10,000 cu ft per sec is equivalent to 1 ft in stage at the elevation reached in these floods.

In the 1947 flood the volume at Chattanooga in the 17-day period, from January 13 to January 29, inclusive, would have amounted to 2,767,000 day-sec-ft. With an allowance for an average base flow of 32,000 cu ft per sec per day this volume is equivalent to a runoff of 3.85 in., or 63% of the rainfall of 6.07 in.

The natural flood volume at Chattanooga for the 14-day period from February 12 to February 25, 1948, inclusive, would have been 2,089,000 day-sec-ft. With an allowance for an average base flow of 46,400 cu ft per sec per day, the flood runoff amounted to 2.50 in. from the rainfall of 3.42 in., or 73%.

In the 1946 flood a peak stage of 35.7 ft was reached at Chattanooga on the morning of January 9. Without the reservoirs this stage would have been

TABLE 5.—PEAK REDUCTIONS AT SOME TENNESSEE VALLEY AUTHORITY DAMS AND RIVER GAGES

Location	Natural Peak		Actual Peak		Reduction	
	Discharge, in cubic feet per second	Stage, in feet	Discharge, in cubic feet per second	Stage, in feet	Discharge, in cubic feet per second	Stage, in feet
(a) 1946 Flood						
Cherokee	64,800	943.2	21,900	931.3	42,900	11.9
Douglas	95,900	892.5	21,200	877.3	74,700	15.2
Knoxville	136,000	824.3	50,000	814.5[a]	86,000	9.8
Fort Loudoun	138,000	765.0	65,000	752.3	73,000	12.7
Fontana	44,800	1,287.0	18,700	1,282.5	26,100	4.5
Norris	77,500	844.8	21,200	831.5	56,300	13.3
Watts Bar	281,000	705.6	163,000	694.0	118,000	11.6
Hiwassee	19,600	1,279.5	13,800	1,280.4[a]	5,800	− 0.9
Chickamauga	301,000	669.4	208,000	659.4	93,000	10.0
Chattanooga	320,000	45.8	222,000	35.7	98,000	10.1
Hales Bar	319,000	626.3	226,000	618.3	93,000	8.0
Guntersville	320,000	581.9	260,000	577.6	60,000	4.3
Wheeler	380,000	508.8	332,000	508.7[a]	48,000	0.1
Wilson	380,000	431.0	348,000	428.7	32,000	2.3
Florence	380,000	429.2	348,000	426.2	32,000	3.0
Pickwick	380,000	397.5	365,000	395.9	15,000	1.6
Savannah	....	394.3	....	391.6	....	2.7
Kentucky	357,000	338.6	400,000	337.3	− 43,000	1.3
Paducah	....	334.5	....	332.2	....	2.3
Cairo	....	53.5	....	52.1	....	1.4
(b) 1947 Flood						
Cherokee	63,000	942.9	18,800	930.2	44,200	12.7
Douglas	86,900	891.2	22,900	877.8	64,000	13.4
Knoxville	130,000	823.4	48,600	813.6[a]	81,400	9.8
Fort Loudoun	125,000	766.5	52,800	751.4	72,200	15.1
Fontana	55,500	1,288.7	16,700	1,282.0	38,800	6.7
Norris	52,000	839.0	21,000	831.5	31,000	7.5
Watts Bar	254,000	703.2	127,500	690.9	126,500	12.3
Hiwassee	35,800	1,284.5	14,300	1,280.2[a]	21,500	4.3
Chickamauga	285,000	667.9	160,000	655.3	125,000	12.6
Chattanooga	307,000	44.5	188,000	31.8	119,000	12.7
Hales Bar	309,000	625.7	199,000	615.7	110,000	10.0
Guntersville	301,000	580.7	227,000	575.7	74,000	5.0
Wheeler	344,000	508.7	295,000	509.1[a]	49,000	− 0.4
Wilson	345,000	429.5	315,000	428.1	30,000	1.4
Florence	345,000	427.6	315,000	424.8	30,000	2.8
Pickwick	343,000	395.4	318,000	390.9	25,000	4.5
Savannah	....	391.4	....	383.7	....	7.7
Kentucky	307,000	332.8	303,000	330.0	4,000	2.8
Paducah	....	327.4	....	325.6	....	1.8
Cairo	....	42.7	....	41.1	....	1.6
(c) 1948 Flood						
Cherokee	47,500	939.0	7,000	925.9	40,500	13.1
Douglas	48,800	884.3	19,500	876.8	29,300	7.5
Knoxville	104,000	819.1	41,000	812.6[a]	63,000	6.5
Fort Loudoun	109,000	760.0	49,500	749.9	59,500	10.1
Fontana	27,200	1,284.2	4,900	1,279.0	22,300	5.2
Norris	66,700	842.4	6,000	826.8	60,700	15.6
Watts Bar	260,000	703.9	193,000	696.0	67,000	7.9
Hiwassee	22,800	1,280.6	3,600	1,278.9[a]	19,200	1.7
Chickamauga	287,000	668.2	196,000	657.6	91,000	10.6
Chattanooga	305,000	44.3	205,000	33.8	100,000	10.5
Hales Bar	297,000	624.8	194,000	617.6	103,000	7.2
Guntersville	293,000	580.1	244,000	577.2	49,000	2.9
Wheeler	349,000	508.8	326,000	509.0[a]	23,000	− 0.2
Wilson	359,000	430.1	380,000	432.0	− 21,000	− 1.9
Florence	359,000	428.2	380,000	429.2	− 21,000	− 1.0
Pickwick	394,000	397.6	411,000	396.1	− 17,000	1.5
Savannah	....	394.4	....	392.3	....	2.1
Kentucky	378,000	339.7	444,000	338.9	− 66,000	0.8
Paducah	....	334.0	....	332.0	....	2.0
Cairo	....	48.7	....	46.75	....	1.95

[a] Tailwater elevations of these projects are greatly affected by normal pool level of downstream projects.

45.8 ft on January 10, or 10.1 ft higher than the actual. On the basis of a survey[3] made in 1938, damage of $6,500,000 would have been suffered, but this was almost entirely eliminated by the operation of the reservoirs. This sum was $11,800,000 under conditions and values existing at the date of the flood as determined by a house-to-house survey, made in 1948, of new construction since 1938 and by an estimated increase in the dollar value of development as of 1938.

In the 1947 flood the actual peak stage was 31.8 ft on January 20, and the natural peak would have been 44.5 ft 2 days later. This reduction of 12.7 ft prevented damages of $11,500,000 under 1947 conditions.

In 1948 the flood reached a stage at Chattanooga of 33.8 ft on February 14. Without the reservoirs the stage would have been 44.3 ft on February 15. This flood would have been the seventh highest at Chattanooga, and would have established the unique occurrence of three major floods in three consecutive years. The reduction in stage of 10.5 ft was worth $12,900,000 in averted damages under 1948 conditions, and made the total reduction in damage at Chattanooga from all floods including several smaller ones since 1936 about $42,000,000.

On the Tennessee River below Kentucky Dam the February, 1948, flood crest would have been 378,000 cu ft per sec without the reservoirs, and would have been exceeded in crest discharge only by the floods of 1897, 1882, 1875, and 1867.

At Cairo a peak stage of 52.1 ft was reached on January 17, January 18, and January 19, 1946. This flood was the highest that had occurred at Cairo so early in the year. Without the reservoirs it has been computed that the peak would have been 53.5 ft. The reduction of 1.4 ft represents a saving in damages downstream from Kentucky Dam of about $500,000 which is a relatively small amount because of the time that the flood occurred. Had the same flood occurred in April or May the saving would have been as much as five times greater for the same reduction.

TABLE 6.—COMPARISON OF FLOODS AT CHATTANOOGA, TENN.

Flood	Rainfall, in inches	Duration, in days	Flood runoff,[a] in inches	Crest stage, in feet
March, 1875	11.40	7	6.94	53.8
April, 1886	9.47	7	6.63	52.2
March, 1917	5.20	5	3.54	47.7
April, 1920	4.90	5	3.30	43.6
January, 1946	4.85	4	3.50	45.8[b]
January, 1947	6.07	6	3.85	44.5[b]
February, 1948	3.42	3	2.50	44.3[b]

[a] After subtracting a base flow. [b] Computed natural stage.

At Cairo a flood crest of 46.75 ft was reported on February 23, 1948, which under natural conditions would have been 48.7 ft on February 24. Such a flood stage is not serious on the lower Ohio and Mississippi rivers at this time of the year and no crop damage was caused.

At many other points on the Tennessee Basin serious damages were prevented during these floods. Below each of the major tributary dams natural crest stages were greatly reduced, the reduction amounting to as much as 15.6 ft below Norris Dam in the 1948 flood. At Knoxville peak stages were reduced by 9.8 ft in both 1946 and 1947. No estimate of the damages prevented at these points has been made.

[3] "The Chattanooga Flood Control Problem," *House Document No. 91*, 76th Cong., 1st Session, 1939.

Comparison with Other Floods

Table 6 shows the rainfall, runoff, and crest stage of seven floods at Chattanooga; and hydrographs of all except the floods of 1875 and 1886 are shown in Fig. 10. The storms producing these floods, however, were much different in their intensities and areal distribution; and only a general comparison can be made between average rainfall and crest stage. The 1917 storm was more

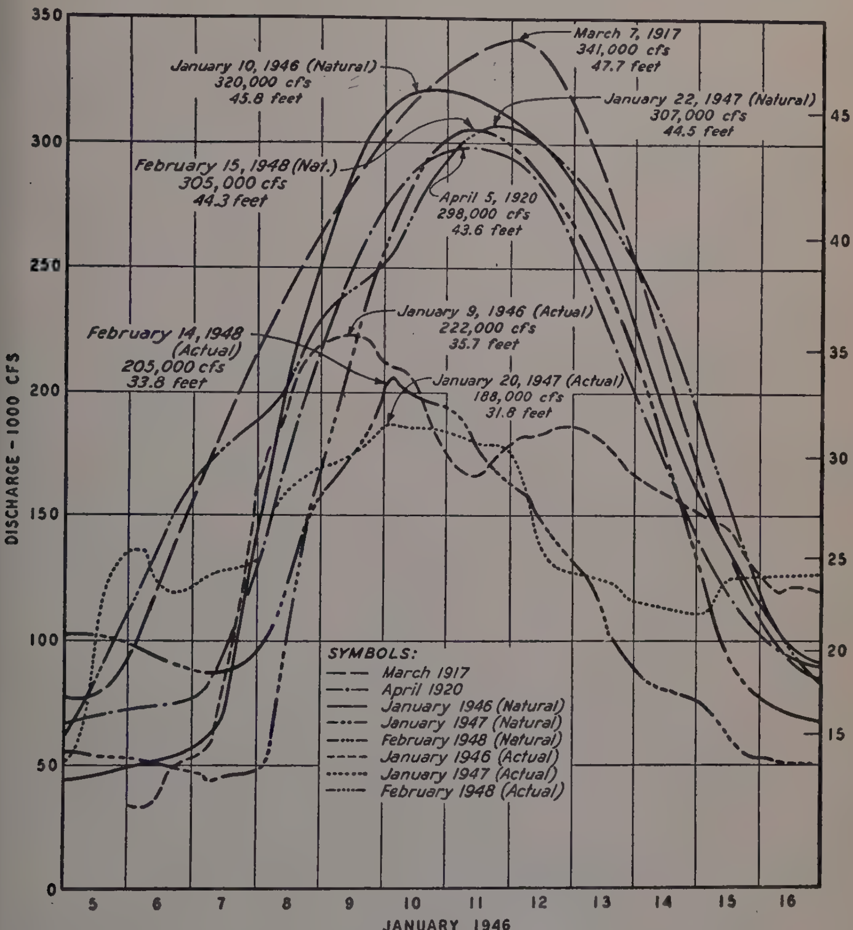

Fig. 10.—Comparison of 1917, 1920, 1946, 1947, and 1948 Floods at Chattanooga, Tenn.

uniform with respect to time and area than any of the others. The 1920 storm was greater over the southern part of the basin than over other parts, and most of the rain occurred in 2 of the 5 days. In January, 1946, there was a period of 3 days with only minor rainfall between two separate storms and the flood crest would have been produced by the first 3 days of rain. The 1947

storm was similar to the 1917 storm but the rate of rainfall per day was less than in 1917. The 1948 storm, although having the lowest total rainfall of any of the five storms, produced a crest stage comparable with the others because of the high concentration of rain on the areas close to Chattanooga, particularly on the Emory River.

TABLE 7.—HIGHEST ELEVEN FLOODS ON LOWER TENNESSEE RIVER

Order	Date	Stage at Johnsonville, Tenn., in feet	Discharge, in cubic feet per second
1	March 24, 1897	48.5	475,000
2	January 31 to February 2, 1882	47.9	447,000
3	March 7, 1875	46.0	447,000
4	March 22, 1867	45.3	416,000
5	February 21, 1948[a]	....	378,000
6	February 21, 1884	43.4	377,000
7	March 20, 1884	41.4	373,000
8	April 15–16, 1886	42.1	372,000
9	January 3–4, 1927	41.0	367,000
10	March 31, 1899	40.2	360,000
11	January 18, 1946[a]	....	357,000

[a] Computed natural flow at Kentucky Dam.

As stated, the flood of February, 1948, would have been the seventh highest flood since 1867, being exceeded by the floods of 1867, 1875, 1886, 1917, 1946, and 1947. Never before have three large floods occurred in three consecutive years; but in 1917, 1918, and 1920 floods occurred which reached crest stages of 47.7 ft, 42.7 ft, and 43.6 ft, respectively.

Under natural conditions the February, 1948, flood would have been the fifth highest on the lower Tennessee River. It is difficult to make an accurate comparison of floods on this section of the river before and after the reservoirs because present stages at the Johnsonville (Tenn.) gage are not comparable with previous stages. A comparison may be made, however, between discharges at Johnsonville for pre-reservoir floods and computed natural discharges at Kentucky Dam for recent floods. Table 7 lists the highest eleven floods arranged in descending order of crest discharge.

ACCELERATION OF FLOODS

A comparison of the natural and actual hydrographs given in Figs. 4 to 9 shows the acceleration of the 1946 flood produced by operation of the main-river reservoirs. At Fort Loudoun Dam the large storage effect of Cherokee and Douglas reservoirs offsets any acceleration. Beginning with Watts Bar Reservoir, however, the actual hydrograph rises more rapidly than the natural hydrograph, and the difference between the two becomes progressively greater as the flood passes downstream. The peak reduction in discharge afforded by the tributary dams also becomes less until at Pickwick Dam in the 1946 flood the reduction is only 15,000 cu ft per sec as compared with 98,000 cu ft per sec at Chattanooga. At Kentucky Dam the acceleration was further increased by drawdown and in the 1946 flood the actual discharge exceeded the computed natural discharge by a substantial amount. From January 6 to January 14, 1946, a volume of 1,400,000 acre-ft was discharged which, under natural conditions, would still have been in the Tennessee River and discharged later.

A similar acceleration occurred in the 1947 and 1948 floods as shown by the difference between the rising limbs of the natural and actual hydrographs. In these floods, because of the relatively large volume stored in the tributary reservoirs, the acceleration was not substantial down to Chattanooga. Below this point, however, the acceleration became more pronounced. At Kentucky Dam a volume of 1,110,000 acre-ft was discharged between January 16 and January 25, 1947, which under natural conditions would still have been in the Tennessee River and discharged later. This acceleration was beneficial to stages on the Ohio and Mississippi rivers; and, when followed by filling to normal level at the time of the Ohio River crest stage, a substantial reduction was produced.

A computation was made to determine whether the 1946 flood could have been accelerated a greater amount. The only method by which this could have been accomplished was by drawing each reservoir to its minimum allowable headwater level and holding that level throughout the flood. It was found that some further acceleration would have been possible by this method, particularly on January 6 and January 7; but it would have required a knowledge of the size of the flood on January 5, when the storm was only beginning. Some of the additional acceleration would have been lost as the floodwater passed through Hales Bar and Wheeler reservoirs where the spillway capacity is limited at the lower levels, and also as it passed through the long (184 miles) Kentucky Reservoir reach. At Kentucky Dam the additional acceleration would have diminished to only a small amount and it can be stated, therefore, that the 1946 flood could not have been accelerated more than it actually was.

This accelerating effect of main-river reservoirs has been known for some time. In the early studies of the Tennessee Basin made by the Corps of Engineers and in all operation studies made by TVA it became apparent that this acceleration would occur and that it was an extremely desirable condition for the regulation of most floods on the Ohio and Mississippi rivers. The ability to discharge large volumes of floodwater from the Tennessee River earlier than under natural conditions and ahead of the crest on the Ohio River is a method of preserving storage capacity for use at the time of the Ohio River crest. The acceleration is caused, of course, by holding the headwater level constant, or by lowering it, at the time of high inflows. The effect of this operation is to decrease the amount of inflow going into storage and, as a result, to increase the amount appearing as discharge.

Operation According to a Fixed Rule

A study of operation of the main-river reservoirs above Chattanooga according to a fixed rule was made to discover whether an improvement could have been made over the actual operation. Under the assumed fixed rule, releases at Chickamauga, and also at Watts Bar and Fort Loudoun, depend on the Chattanooga stage and the Chickamauga headwater level, no knowledge of the rainfall or prediction of inflow being required. The rule was planned so that complete use would be made of the available storage in Chickamauga, Watts Bar, and Fort Loudoun reservoirs during a flood equal to the maximum of record, which was about 12 ft higher at Chattanooga than the flood of

January, 1946. When it is recognized that a flood is developing, the operation would be as follows:

1. Hold the normal headwater level at Chickamauga (El. 675) until a 20-ft stage is reached on the Chattanooga gage.
2. Increase the stage, not exceeding 30 ft, attempting to lower Chickamauga headwater to the minimum level, El. 673.
3. Continue the 30-ft stage until the Chickamauga headwater elevation, El. 677, is reached.
4. Increase the stage to 31 ft and hold it until the headwater elevation, El. 678, is reached.
5. Make successive 1-ft increases in the Chattanooga stage for each 1-ft rise in the Chickamauga headwater elevation until, with a 38-ft stage, the headwater elevation, El. 685, is reached.
6. Hold El. 685 until the peak of the flood is past and then promptly return the reservoir to normal level with a decreasing rate of release from Chickamauga Reservoir.
7. Hold the normal headwater level at Watts Bar and Fort Loudoun reservoirs until a stage of 20 ft is reached at Chattanooga. Thereafter, up to the time of the Chickamauga peak, hold discharges at 0.7 and 0.4, respectively, of the Chattanooga allowable discharge, unless they are limited because of minimum headwater or full reservoir. (By "allowable discharge" is meant the discharge indicated for the Chattanooga stage and the Chickamauga headwater level.)
8. When the headwater elevation begins to recede, return the three reservoirs to normal levels at rates consistent with flood conditions on the lower Tennessee River.

The foregoing rules were applied to the three floods in 1946, 1947, and 1948 as far as possible, assuming that the actual tributary operation would be repeated and that the normal headwater elevation would be maintained prior to the flood. The rule for release, at Fort Loudoun, of four tenths of the Chattanooga discharge could not be used because of the relatively low flows at Fort Loudoun. That reservoir was drawn to the minimum level and held there until the flood danger was past.

A comparison (see Figs. 4 and 5 and Table 8) of the fixed-rule operation with the actual operation shows that the maximum headwater levels in the three reservoirs were lower with fixed-rule operation. In the 1946 flood the peak stage at Chattanooga would have been 33 ft instead of an actual stage of 35.7 ft. The greater reduction would be obtained by increasing the release earlier and thereby holding the available storage for later filling. It is realized, of course, that there would be objections to the sudden increase from 20 ft to 30 ft even if it were physically possible to open the gates (actually the stage increased from 20 ft to 30 ft in about 18 hours), but it should always be borne in mind that the sooner the 30-ft stage is reached, the lower the peak may be made later.

For the 1947 and 1948 floods the fixed-rule operation would give only a small additional reduction (0.8 ft) at Chattanooga below the actual crest stage. The three main-river reservoirs, however, would have been in better condition for retaining additional flood flows if they had occurred, because of the lower headwater levels.

TABLE 8.—COMPARISON OF OPERATIONS FOR CHATTANOOGA, TENN.

RESERVOIR OPERATION		1946 FLOOD[a]			1947 FLOOD[a]			1948 FLOOD[a]		
Tributary	Main river	Chickamauga	Chattanooga		Chickamauga	Chattanooga		Chickamauga	Chattanooga	
			Flow	Stage		Flow	Stage		Flow	Stage
(1)	(2)	(3)	(4)	(5)	(3)	(4)	(5)	(3)	(4)	(5)
Natural	Natural	301	320	45.8	285	307	44.5	287	305	44.3
Actual	Natural	222	244	38.1	176	202	33.4	216	239	37.5
Actual	Actual	208	222	35.7	160	188	31.8	196	205	33.8
Actual	Fixed rule	181	198	33.0	162	181	31.0	171	198	33.0
Actual	Ideal	123	153	27.5	97	123	23.7	80	111	22.1

[a] Cols. 3 and 4 contain the maximum discharge, in thousands of cubic feet per second, and Col. 5 contains stage heights, in feet.

Operation of the tributary reservoirs according to a fixed rule also has been given considerable study. A tentative guide curve has been developed by which tributary reservoir discharges would be determined by reservoir stages. In the floods of 1946, 1947, and 1948, operation according to the tentative fixed rule would vary only slightly from the actual operation.

OPERATION OF MAIN-RIVER RESERVOIRS FOR MAXIMUM POSSIBLE REDUCTION

In addition to the study of the main-river reservoirs above Chattanooga according to a fixed rule, an investigation was made of an operation in which it was assumed that complete knowledge of the inflow would be available and that full use would be made of flood-control storage. As in the fixed-rule study, it was also assumed that the tributary reservoirs would have been operated as they actually were. This operation shows the results which could be approached if the "ideal" were realized. However, it seems almost impossible that such complete knowledge will ever be available in advance for a flood of major proportions, and this method merely indicates the possible results of "hindsight" operation.

This ideal operation consisted of drawing each main-river reservoir to its minimum level, provided the discharge did not exceed the peak rate produced later, and then of holding that level if possible until the discharge increased to a rate which, if maintained, would cause the reservoir level to rise to the maximum permitted. Such an operation requires a knowledge of the inflow and produces a flat-peak discharge below each dam. At Kentucky Reservoir a modification of the operation was made. Instead of producing a flat discharge below the dam, the reservoir was filled by releasing water at rates that would produce a flat peak at Cairo. The reservoirs were returned to their

normal levels at rates consistent with downstream flood conditions. In the case of the 1946 flood the reservoirs were held full until there was no possibility that the releases would affect Cairo stages. In the 1947 flood they were returned to normal levels immediately by making the discharges equivalent to a 30-ft stage at Chattanooga.

Figs. 4 to 9 for the 1946 flood show, at each dam and at Chattanooga, Paducah, and Cairo, the results of the ideal reservoir operation. Hydrographs for the natural condition and for other operations are also given for comparison. The maximum stage in the 1946 flood at Chattanooga with ideal operation of main-river reservoirs was 27.5 ft; and, at Cairo, 47.4 ft. In the 1947 flood the stage at Chattanooga would have been 23.7 ft with the ideal operation; and, in the 1948 flood, it would have been 22.1 ft. Because of the relatively small magnitude of the 1947 flood at Cairo, studies of hypothetical reservoir operation were not made below Chattanooga.

Effect of Tributary Reservoirs on Chattanooga Stage

The effect, at Chattanooga, of the tributary reservoirs alone was determined by assuming that the main-river reservoirs were not built—that is, that natural conditions would exist in the Tennessee River. It was also assumed that tributary reservoir operation would be the same as the actual operation. The difference between the hydrograph thus computed and the natural hydrograph indicates the effect of the tributary reservoirs, and a comparison with the actual hydrograph shows the effect of the three main-river reservoirs.

Peak discharges and stages for the three floods computed on the foregoing assumptions are shown in Table 8 together with peaks for other conditions for comparison. Hydrographs of the 1946 flood are shown in Figs. 4 and 5.

It will be noted from Table 8 that in the 1946 flood the tributary reservoirs reduced the flood at Chattanooga from stage 45.8 to stage 38.1, or 7.7 ft, and that the three main-river reservoirs provided additional reduction to stage 35.7, or 2.4 ft. However, if greater use of the main-river storage had been made, greater reduction would have been possible, as indicated by the ideal operation. Operation according to the fixed rule also would have given a greater reduction because of the more efficient use of storage.

In the 1947 flood the tributary reservoirs reduced the flood from a stage of 44.5 ft to one of 33.4 ft, or 11.1 ft. The main-river reservoirs provided additional reduction to 31.8 ft or to 1.6 ft. In the 1948 flood the tributary reservoirs were responsible for a reduction of 6.8 ft and the main-river reservoirs for a reduction of 3.7 ft.

Effect of Reservoirs on Cairo Stage in the 1946 and 1948 Floods

Operation of all reservoirs above Chattanooga was assumed in this study as being primarily for the control of the flood at that point. It is desirable to know the effect of this operation at Cairo, and also the effect of operating the lower Tennessee River reservoirs. To compute these effects, two additional routing studies were made. In one the effect at Cairo of all reservoirs above Chattanooga was determined by assuming that there were no reservoirs below Hales Bar—that is, that actual discharge at Hales Bar combined with inflows

below that point was carried downstream to Cairo under natural conditions. The difference between this hydrograph and the natural hydrograph indicates the effect of the reservoirs on the upper river.

In the second routing study, Guntersville, Wheeler, and Pickwick reservoirs were added, only Kentucky Reservoir being considered nonexistent. When the Cairo stage, computed for this condition, is compared with the hydrograph for reservoirs above Hales Bar, it shows the effect of Guntersville, Wheeler, and Pickwick reservoirs. When the Cairo stage is compared with the actual hydrograph, the effect of Kentucky Reservoir is obtained.

TABLE 9.—COMPARISON OF OPERATIONS FOR CAIRO, ILL.

Operation of reservoir system	1946 Flood				1948 Flood			
	Kentucky		Paducah	Cairo	Kentucky		Paducah	Cairo
	Discharge[a]	Tailwater elevation	Elevation	Stage, in feet	Discharge[a]	Tailwater elevation	Elevation	Stage, in feet
(1)	(2)	(3)	(4)	(5)	(2)	(3)	(4)	(5)
Natural	357	338.6	334.5	53.5	378	339.7	334.0	48.7
Reservoirs Down to—								
Hales Bar Dam	333	337.5	333.8	53.2	357	338.0	332.8	47.8
Pickwick Dam	356	337.6	333.6	53.1	372	337.6	332.4	47.7
All Reservoirs—								
Actual operation	400	337.3	332.2	52.1	444	338.9	332.0	46.7
Ideal operation of main-river reservoirs	364	335.0	327.4	47.4	439	338.1	330.6	43.5

[a] Discharges, in thousands of cubic feet per second.

Table 9 shows peak discharge at Kentucky Dam and peak stages at Paducah and Cairo for the various conditions. Hydrographs are shown in Figs. 6 to 9 for the 1946 flood. In the 1946 flood all reservoirs above Hales Bar Dam caused a peak reduction at Cairo of 0.3 ft; Guntersville, Wheeler, and Pickwick produced an additional reduction of 0.1 ft; and Kentucky, a reduction of 1.1 ft. The reduction of 0.1 ft attributed to Pickwick, Wheeler, and Guntersville reservoirs is small—almost negligible—but available storage was not completely filled because the flood did not reach critical stages at Cairo. It should also be noted in Table 9 that the regulated peak discharge from Kentucky Dam was greater than the natural peak discharge, but that the peak stage downstream was less. This result is possible, of course, only if the increased flows do not coincide with the Ohio River peak. Hydrographs in Fig. 9 also show that the major effect of upstream regulation appears after the Cairo peak and that Kentucky Reservoir is most effective on the peak, as would be expected.

Flood of April, 1948, at Cairo

The aforementioned three floods of 1946, 1947, and 1948 are examples of floods that occur during the winter or spring flood season on the Tennessee Basin, and which have relatively high flows in the Tennessee River and relatively low flows in the Ohio and Mississippi rivers. In such cases the tributary reservoirs store a large proportion of their inflow; and, if the water levels rise

above normal elevations, they are returned to normal within a short time, usually in about 2 weeks. Moreover, moderately high stages may occur in the Mississippi River at this time of the year without causing any crop damage.

Floods of a different type, in which flows are relatively low in the Tennessee River and relatively high in the Ohio and Mississippi rivers and which occur later in the season when agricultural operations have begun, present different problems in reservoir operation. During these floods storage probably will be retained in the tributary reservoirs and not released until late in the year. The retention of tributary inflow over a period of months, combined with storage in the main-river reservoirs and the positive regulation afforded by Kentucky Reservoir, will reduce stages at Cairo over a long period. In addition to preventing the flooding of some agricultural lands, other lands may be entered and worked sooner than under natural flood conditions.

An example of this type of flood was that of April, 1948. Stages at Cairo began to rise above 30 ft about the middle of March and reached a crest stage of 51.6 ft on April 3 (see Fig. 11). Without the reservoirs the crest would have been 53.4 on April 4. Stages then fell until April 12 when, following heavy rainfall on the upper Ohio River, a second crest stage of 47.9 ft was reached on April 23, April 24, and April 25. Without the reservoirs this crest would have been 49.0 ft on April 21. Drawdown of Kentucky Reservoir was commenced on March 23 when it was certain that the Cairo stage would continue to rise above 40 ft, but the headwater level was returned to El. 354 when predictions did not indicate serious crest stages. On April 2, Kentucky Reservoir discharge was reduced to turbine capacity (60,000 cu ft per sec) and this rate was maintained for 7 days throughout the crest period at Cairo.

Kentucky Reservoir discharge was increased when Cairo stages fell below 50 ft to lower the headwater level. To regulate the second crest on April 23, April 24, and April 25 the discharge was reduced from 145,000 cu ft per sec on April 16 to 60,000 cu ft per sec on April 19 and this was not exceeded for the remainder of the crest period at Cairo. The natural Cairo crest would have been 49.0 ft on April 21. The reduction of 1.8 ft in the first crest represents about $1,000,000 in averted damages, and in the second crest the reduction of 1.1 ft represents about $600,000 in averted damages.

TABLE 10.—INFLOW, OUTFLOW, AND STORAGE IN TRIBUTARY RESERVOIRS OF THE TENNESSEE VALLEY AUTHORITY (IN THOUSANDS OF ACRE-FEET) DURING THE 43-DAY PERIOD CORRESPONDING TO MARCH 25–MAY 6 AT CAIRO, ILL.

Reservoir	Inflow	Outflow	Storage
Cherokee	725	304	421
Douglas	860	518	342
Fontana	548	176	372
Norris	785	319	466
Hiwassee	268	87	181[a]
Total	3,186	1,404	1,782

[a] Includes storage in Chatuge and Nottely reservoirs.

Actual stages at Cairo were lower than natural stages from March 25 to May 6. Except for power generation releases the entire tributary inflows were stored during a corresponding period, as shown in Table 10.

The tributary reservoirs stored 1,782,000 acre-ft or about 56% of their inflow during the 43-day period corresponding to March 25–May 6 at Cairo. This storage is equivalent to an average discharge of about 21,000 cu ft per sec.

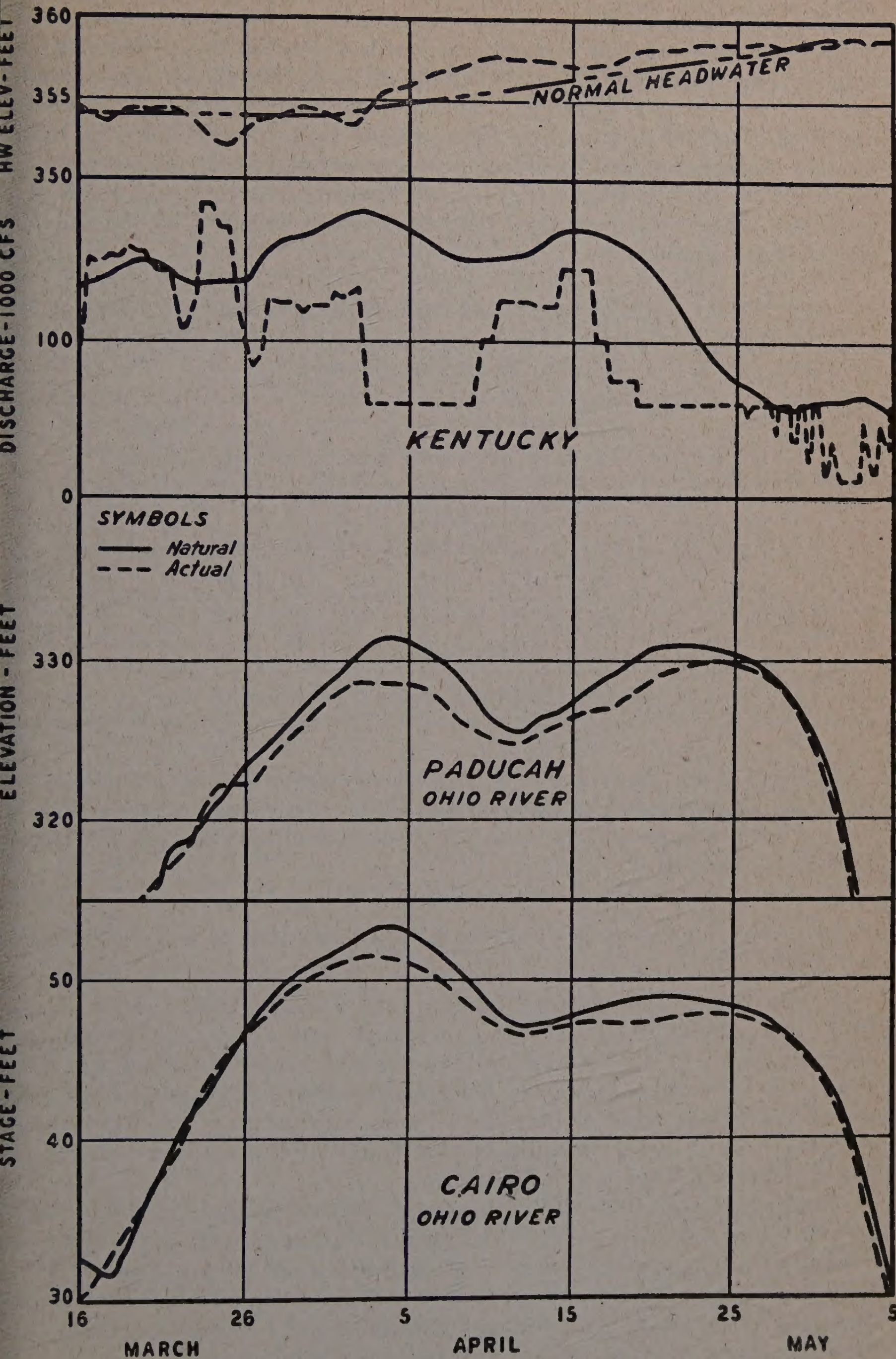

Fig. 11—Effect of Operation of Tennessee Valley Authority Reservoirs on Stages at Paducah, Ky., and Cairo, Ill.; Floods of April, 1948

The main Tennessee River reservoirs also were being filled from their flood-season levels to their maximum normal levels within this period and the total amount stored was 2,041,000 acre-ft, of which 898,000 acre-ft, or 44%, occurred in Kentucky Reservoir. This storage is equivalent to an average discharge of 24,000 cu ft per sec during the 43-day period, making the total average discharge retained by the reservoir system equal to 45,000 cu ft per sec, which is equivalent to about 1 ft at Cairo. Regulation by Kentucky Reservoir produced greater crest reductions than the average indicated by the storage over a 43-day period.

TABLE 11.—Crest Stages and Crest Reductions (in Feet); Flood of April, 1948 (Discharges Are in Thousand Cubic Feet Per Second)

Location	April 3, 1948						April 23, 1948					
	Natural Crest		Actual Crest		Reduction		Natural Crest		Actual Crest		Reduction	
	Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage	Flow	Stage
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(2)	(3)	(4)	(5)	(6)	(7)
Kentucky...	180	332.9	131[a]	329.8	49	3.1	170	331.9	146[a]	330.2	24	1.7
Paducah, Ky.	....	331.4	....	328.7	....	2.7	....	331.0	....	330.0	....	1.0
Cairo, Ill.....	....	53.4	....	51.6	....	1.8	....	49.0	....	47.9	....	1.1

[a] Prior to the reduction of the outflow to turbine capacity.

Table 11 gives the natural and actual flood crests and crest reductions at Kentucky Reservoir and at Paducah and Cairo. No computations of hypothetical operations were made for this flood because of the relatively low flows on the Tennessee River.

Conclusions

The results of the studies reported in this paper lead to five conclusions, as follows:

1. The crest stage of floods of January, 1946, January, 1947, and February, 1948, were reduced 10.1 ft, 12.7 ft, and 10.5 ft, respectively, at Chattanooga by the operation of the TVA reservoir system and, in the 1946 flood, to 1.5 ft at Cairo. These reductions prevented damages of $37,100,000 at Chattanooga and of about $500,000 below Kentucky Dam. Reductions of two flood crests at Cairo in April, 1948, amounting to 1.8 ft and 1.1 ft prevented damages of about $1,600,000 below Kentucky Dam.

2. The reductions below the natural crest at Chattanooga in the 1946, 1947, and 1948 floods were about 55%, 61%, and 47%, respectively, of the greatest possible reduction, and at Cairo in the 1946 flood the reduction was about 25%. It should be recognized, however, that reductions as large as indicated to be possible by the "ideal" operation neither were needed nor were practicable in the 1946 flood in view of continued predictions of rainfall.

3. If a fixed rule of operation had been followed with the three main-river reservoirs above Chattanooga, an additional reduction of 2.7 ft would have been possible at that point in the 1946 flood, and the reservoirs would have been in as good condition for storing inflow from possible additional rainfall as they actually were when the crest had passed. In the 1947 flood and the 1948 flood the fixed-rule operation would have given only a slightly greater reduction than was actually obtained.

4. The acceleration of the flood by main-river reservoirs is indicated to have occurred as was revealed by the early planning studies. Natural storage capacity of the Tennessee River normally had an adverse effect on Ohio River flood crests because of the relative timing of the flood waves. The elimination of part of this storage by the operation of the main-river dams has contributed substantially to the reduction of Ohio River peaks. The use of reservoir storage at the time of the Ohio River crest has reduced those peaks still further.

5. Reductions in Cairo stages will occur over long periods when the TVA reservoirs are being filled to maximum normal levels after the flood season in the Tennessee Basin. If this filling is coincident with floods on the Ohio and Mississippi rivers, there will be a substantial saving in damages, as in the flood of April, 1948. Even with the reservoirs filled to maximum normal level a large amount of storage would be available (particularly in Kentucky Reservoir) to regulate a large flood at Cairo.

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